

Explanations on the onset and damping behaviors in a standing-wave thermoacoustic engine



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HIGHLIGHTS

- A thermodynamics analysis is carried out to understand the onset process.
- A new explanation is proposed to understand the onset and damping behaviors.
- The experimental results at different tilted angles confirms the explanations.

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ABSTRACT

In order to understand the onset and damping behaviors of the thermoacoustic engine, a series of experiments and a simplified thermodynamics analysis are carried out. It is found that both the efficiency and the acoustic power of the gas increase with the increase of the gas-stack heat transfer coefficient, the gas displacement amplitude and the heating difference. Before onset, since the gas-stack heat transfer coefficient of natural convection and the amplitude of the gas are very low, a higher temperature difference is required to produce enough acoustic power to overcome the thermal and viscous dissipation and to excite oscillation. In the damping process, the gas-stack heat transfer coefficient and the amplitude of the gas are much higher because of the thermoacoustic oscillation. So a lower temperature difference is required to maintain the oscillation. In order to further verify this analysis, the experimental investigations are carried out at different tilted angles ranging from 90° to -90° . As the tilted angle decreases, the gas-stack heat transfer coefficient of the natural convection increases. The experimental results show that both the onset and damping temperature differences decrease with the decreasing of the tilted angle, which further confirms the above explanations.

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1. Introduction

Thermoacoustic engine is novel thermodynamic machinery which converts thermal energy to acoustic power based on the thermoacoustic effect. Compared with traditional engines, thermoacoustic engine has three most important advantages: (1) it has no moving parts except for the working gas undergoing the acoustic motion, which makes the structure simple and highly reliable; (2) the working gas is usually noble gases, such as He, Ar, Xe, N_2 , CO_2 , etc, which are environmentally friendly; and (3) it can be driven by low-grade heat source, including solar energy, industrial waste heat, geothermal energy, etc. These advantages attracted both academic and industrial interests in the last three

decades [1–4]. Thermoacoustic technology (including thermoacoustic heat engine [5], thermoacoustic refrigerator [6], thermoacoustic separation [7], and thermoacoustic electric generator [8]) has made rapid development and will receive more and more attentions in the future. The most powerful thermoacoustic Stirling heat engine has achieved an efficiency of 30%, which is comparable to that of the common internal combustion engines and piston-driven Stirling engines [9].

It is one of the most potential applications for thermoacoustic engine to utilize low-grade heat source to drive a refrigerator [10–13] or electrodynamic linear alternator [8]. Solar energy, which is abundant, pollution-free and inexhaustible, is considered to be the most convenient heat source and has attracted more and more research interests [14,15]. As a result, solar powered thermoacoustic engine, having both the advantages of solar energy and thermoacoustic engine, is expected to have a wide application in the future. The first solar-driven thermoacoustic engine was

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designed and constructed by Chen and Garrett in 1998 [16]. The measured sound pressure level can reach 120 dB easily on a clear day. After that, they built a large solar powered thermoacoustic cooler [17]. Its acoustic power was generated by solar radiation in the thermoacoustic engine and subsequently used to pump heat from external loads in the thermoacoustic refrigerator. The device achieved cooling although compromised by gas leakage and thermal losses. In 2000, Adeff and Hofler [18] built a solar driven thermoacoustic refrigerator. When the heating temperature was 450 °C, 2.5 W of cooling power was produced at a cold temperature of 5 °C. In order to explore solar thermal electric power generation and solar powered refrigerator, our research group designed a two-axis tracking solar powered thermoacoustic engine in 2009 [19]. However, the self-excited oscillation was impeded and the onset temperature of the thermoacoustic engine was elevated to more than 500 °C for gas leakage and thermal losses. Therefore, it is imperative to investigate the self-excited oscillation process and the onset and damping behaviors of thermoacoustic engine powered by solar energy.

In fact, the onset mechanism of thermoacoustic oscillation is always a hot research topic, because a lower onset temperature means that we can utilize lower-graded heat source. The mechanism of thermoacoustic oscillation has been recognized gradually since the discovery of thermoacoustic effect. In 1887, Rayleigh [20] pointed out that “if heat be given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction, the vibration is encouraged. On the other hand, if heat be given at the moment of greatest rarefaction, or abstracted at the moment of greatest condensation, the vibration is discouraged.” This explanation is referred to as “Rayleigh criterion” and is considered to be a rational explanation of thermoacoustic effect by now. Rayleigh criterion gives a qualitative understanding on how to maintain oscillation in a thermoacoustic engine. Then Rott [21] and Swift [22] gave a quantitative study on the building of thermoacoustic oscillation and proposed “critical temperature gradient” [22], which was the boundary between the heat pump and prime mover functions of thermoacoustic engines.

Since 1992, Atchley et al. [23–25] had conducted series of studies on the onset behavior and a quality factor was proposed to measure the transition to onset in a thermoacoustic prime mover. Arnott et al. [26] showed that the instability occurs when $\bar{W}_s + \bar{W}_{\text{ext}} \geq 0$, where $\bar{W}_s$ is the acoustic power produced in the stack, $\bar{W}_{\text{ext}}$ is the work loss by thermal and viscous dissipation in the system and found the normalized onset temperature gradient.

However, the above researches were based on the assumption that the damping point coincided with the onset point. In 1998, Zhou and Marsubara [27] carried out an experimental study on the onset process of thermoacoustic prime mover and found that the onset and damping temperatures were different from each other.

Then Chen and Jin [28] conducted detailed study on the onset and damping behavior in a thermoacoustic prime mover and found that the damping temperature lagged the onset temperature. Based on this, a hysteretic loop, due to the temperature difference between the onset point and the damping one, was recognized for the first time. This hysteresis phenomenon was discussed by analogy to other phenomena widely found in nature, such as light induced reaction, boiling heat transfer and the magnetization effect. However, no reasonable interpretation had been given on the fundamental cause of the discrepancy between the onset and damping temperatures and the hysteretic loop in thermoacoustic oscillation. In 2003, Yu et al. [29] observed a low frequency mode and a high frequency mode in the onset process of a thermoacoustic Stirling engine. In 2006, Qiu et al. [30] proposed a new method to decrease the onset temperature of thermoacoustic engine by introducing a pressure disturbance. Based on plenty of experimental results, they predicted that the onset temperature should approach the damping temperature under the disturbed condition. Most recently, Wang et al. [31,32] used infrared imaging as a visualization method for the first time to characterize the onset mechanism and found that Gedeon streaming had significant influence on the axial temperature distribution in the onset and damping processes. Numerical simulation method was also used to investigate the onset characteristics in standing wave thermoacoustic engines [33–35].

All of the existing results have greatly promoted the research of the onset and damping mechanisms of thermoacoustic oscillation. However, further explanations are still needed on the fundamental cause of the difference between the onset and damping temperatures, the hysteretic loop in thermoacoustic oscillation, and the decreasing of onset temperature by a pressure disturbance. In order to decrease the onset temperature and improve the thermoacoustic conversion efficiency and apply our solar powered thermoacoustic engine to a thermoacoustic refrigerator, experiments have been performed in a standing-wave thermoacoustic engine in this paper. Firstly, three fundamental questions about the onset and damping phenomena are raised and discussed in detail. Then a simplified thermodynamics analysis is performed and an integrated explanation on the onset and damping behaviors is proposed. Finally, a series of experiments are carried out at different tilted angles ranging from -90° to 90° to further verify the above explanations.

2. Experimental apparatus

The experiments presented in this paper are based on a standing-wave thermoacoustic engine as shown in Fig. 1. The apparatus includes six main parts: hot buffer, hot heat exchanger, parallel-plate stack, cooling heat exchanger, resonance tube, and resonance cavity. Seven temperature sensors are used to measure

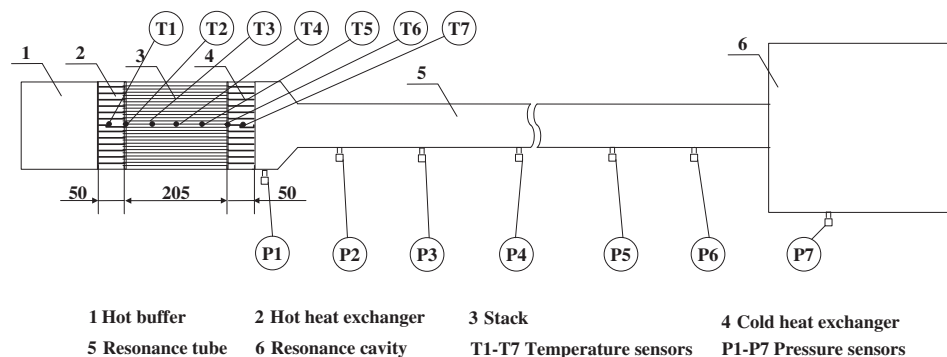


Fig. 1. Schematic of the standing-wave thermoacoustic engine.

the temperature distribution in the thermoacoustic couple. In order to measure the temperature difference, T1 and T7 are located in the hot and cooling heat exchanger, respectively. T2 ~ T6 are evenly located on the parallel-plate stack to measure the temperature distribution along the x -axis. The pressure data are acquired instantaneously by seven pressure sensors: P1 is used to observe the pressure oscillation in the thermoacoustic couple, P2~P6 are evenly located at the resonance tube, and P7 is located at the resonance cavity. The engine is powered by electrical heating rod. Other details of the thermoacoustic engine system are shown in Ref. [19].

3. Results and analysis

3.1. Questions on onset and damping behaviors

In order to investigate the onset and damping behaviors, a series of experiments have been carried out with different working gases. For instance, Helium is first used as the working gas with a filling pressure of 0.7 MPa. Fig. 2 shows the pressure ratio $R = p_{\max}/p_{\min}$ in position P1 with the heating temperature difference of $\Delta T = T_{\text{hot}} - T_{\text{cold}}$, where $p_{\max}$, $p_{\min}$ are respectively the maximum and minimum of the pressure in a period, and T_{hot} , T_{cold} are respectively the temperatures in the hot and cold heat exchangers. In the onset process, the pressure ratio maintains stable until the heating temperature difference exceeds 477 K. In other words, the onset temperature difference is 477 K in this condition. In the damping process, the oscillation is maintained even when the heating temperature difference is less than 477 K. When the heating temperature difference is less than 418 K, the significant pressure oscillation disappears. That is to say that the damping temperature difference is 418 K. Therefore, the difference between the onset temperature and the damping temperature is as high as 59 K. A similar phenomenon can be observed in other experiments. So what is the fundamental cause that makes the onset temperature much higher than the damping one?

In Fig. 2, another anomalous phenomenon in the onset process can be observed. When the heating temperature difference is higher than 477 K, a fast increase of the pressure ratio appears. And then, the pressure ratio increases gradually with increasing heating temperature difference. However, in the damping process, the pressure ratio decreases gradually all along with the heating temperature difference. This phenomenon indicates that the onset of thermoacoustic engine is just like a sudden process, while the damping seems to be a gradual one.

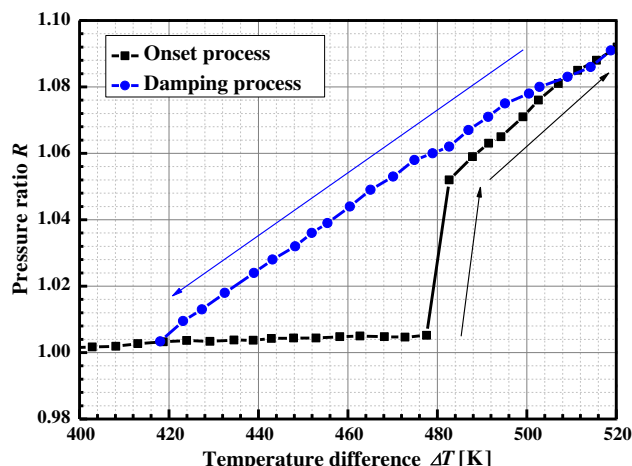


Fig. 2. The pressure ratio in position P1.

In order to further understand the onset and damping processes, the corresponding changes of the temperatures in the heat exchangers and the stack are shown in Fig. 3. It can be seen that the temperatures in the stack decrease suddenly after onset, while the temperatures in the heat exchangers change very little. After 300 s, the maximal decrease of the temperatures in the stack is as high as 37 K. However, no rapid change is observed in the temperatures of the stack in the damping process. So why is the onset of thermoacoustic engine just like a sudden process, while the damping seems is a gradual process?

In the recognizing of the onset mechanism of thermoacoustic oscillation, an effective method to decrease the onset temperature must be mentioned. In 2006, Qiu et al. [30] found that a contrived pressure disturbance could remarkably decrease the onset temperature of thermoacoustic engine, as shown in Fig. 4. In the experiment, nitrogen is used as the working gas with a filling pressure of 0.34 MPa. The onset temperature is about 232 °C in the undisturbed condition, while it is about 215 °C in the disturbed condition. In this experiment, the onset temperature is decreased by 15 K by using a pressure disturbance. Moreover, when a pressure disturbance is introduced to the system, the pressure amplitude increases gradually with the heating temperature and the onset process seems to be a gradual process, which is different from that in undisturbed condition.

The experiments reported in Ref. [30] also showed the similar results. They gave a qualitative understanding on this phenomenon: “When the temperature gradient along the regenerator is large enough, the thermoacoustic system is in an unsteady state in which even a very small pressure disturbance can be magnified. If stimulated by a contrived pressure disturbance, the thermoacoustic system in unsteady state will start in advance.” However, in their other research [36], they found that a pressure disturbance by discharging working gas could make the system onset in advance, while a pressure disturbance by charging working gas had no effect on the onset behavior. This result indicates that the fundamental cause of this disturbance method to decrease the onset temperature may be more complex. So, why a contrived pressure disturbance can remarkably decrease the onset temperature?

Consequently, there are different anomalous phenomena in the onset and damping processes. Combining the three questions, we can find out that they may be deeply related to each other. So the ultimate question is: can a systematic explanation be obtained to understand all these anomalous phenomena?

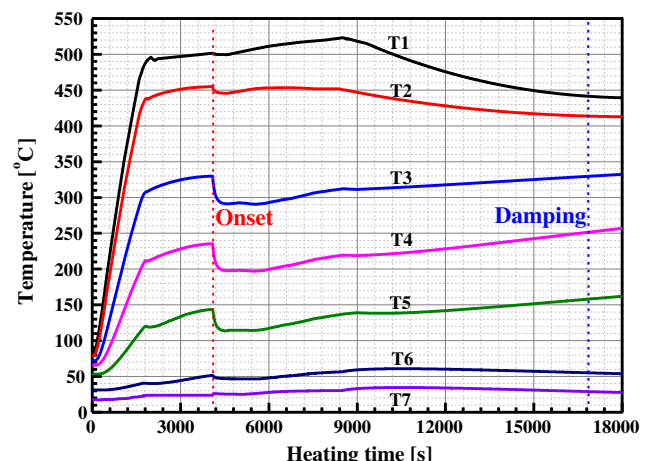


Fig. 3. The temperatures in the thermoacoustic couple as a function of time.

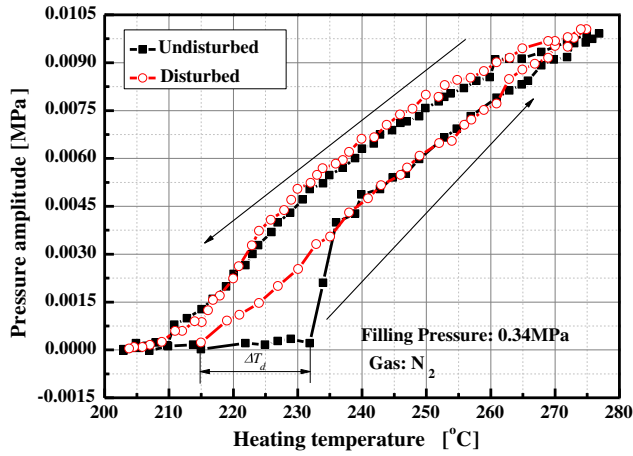


Fig. 4. Comparison of hysteresis loops between undisturbed and disturbed conditions [30].

3.2. Mechanisms of onset and damping behaviors

3.2.1. Thermodynamics analysis of thermoacoustic oscillation

In order to answer the above questions, a simplified thermodynamics analysis should be carried out. In a thermoacoustic engine, if a temperature gradient is established in the stack, the gas parcels will be compressed or expanded near the equilibrium position. Fig. 5 shows the pressure oscillation in the onset process when the filling pressure is 0.7 MPa and helium is used as working gas. It can be seen that the pressure oscillated before onset. The only difference before and after onset is that the pressure amplitude is very low before onset, while it suddenly increases to a high value after onset. Therefore, a unified approach is proposed to analyze the oscillations before and after onset.

Consider a single plate of the stack and a gas parcel, as shown in Fig. 6. The gas parcel is supposed to experience a four-step cycle with two adiabatic and two constant-pressure heat transfers processes [22,37]. In the initial state, the gas parcel is in its right stagnation point and then experiences adiabatic compression to state 2. In the second step, the gas parcel is heated to state 3 by the stack at constant pressure. In the third step, the gas parcel experiences adiabatic expansion to state 4. Finally, the gas parcel releases heat to the stack at constant pressure and returns to state 1. The temperature-entropy chart of this four-step cycle is shown in

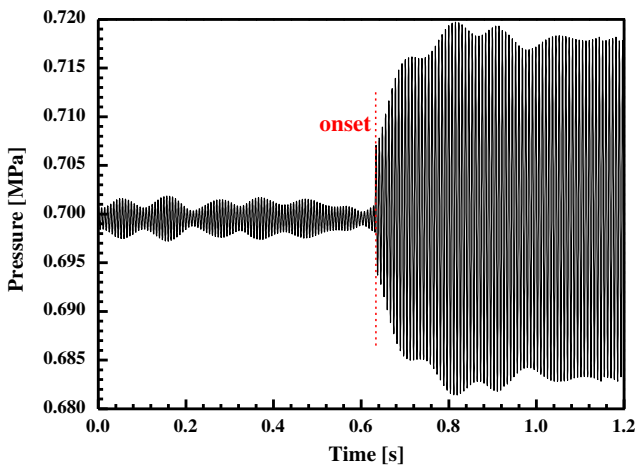


Fig. 5. The pressure oscillation in the onset process.

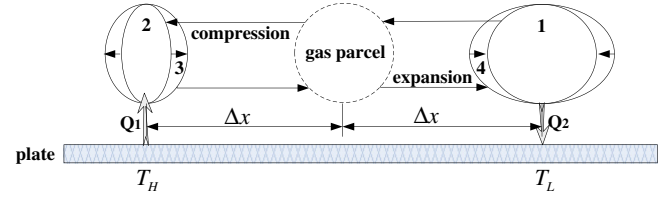


Fig. 6. Typical gas parcel in the stack of the thermoacoustic engine.

Fig. 7. For purposes of analysis, the two constant-pressure heat transfers are simplified to constant-temperature steps. The average hot temperature is $\bar{T}_h = (T_3 - T_2)/\ln(T_3/T_2)$ and the average cold temperature is $\bar{T}_l = (T_4 - T_1)/\ln(T_4/T_1)$. Thus, the four-step cycle is an endo-reversible Carnot cycle. The heat flows of the gas parcel in the hot and cold sides are

$$Q_1 = h_1 a_1 (T_H - \bar{T}_h) t_1 \quad (1)$$

$$Q_2 = h_2 a_2 (\bar{T}_l - T_L) t_2 \quad (2)$$

where h_1 and h_2 are the heat transfer coefficients, a_1 and a_2 are the heat exchange areas, t_1 and t_2 are the heat exchange times in an oscillation cycle, and T_H and T_L are the temperatures in the hot and cold sides of the stack, respectively. For the oscillation cycle of the gas parcel, it is assumed that $h_1 = h_2$, $a_1 = a_2$, $t_1 = t_2$ and $t = \gamma(t_1 + t_2)$, where t is the total time of the cycle and γ is a proportional coefficient. We define the temperature differences between the gas parcel and the stack as $\delta_H = T_H - \bar{T}_h$, $\delta_L = \bar{T}_l - T_L$. So the acoustic power produced by the cycle can be calculated by

$$\eta = \frac{Q_1 - Q_2}{Q_1} = \left(1 - \frac{\delta_L}{\delta_H}\right) \quad (3)$$

$$P = \frac{Q_1 - Q_2}{t} = \frac{h_1 a_1 (\delta_H - \delta_L)}{2\gamma} \quad (4)$$

For Carnot cycle, we have

$$\frac{Q_1}{Q_2} = \frac{\bar{T}_h}{\bar{T}_l} \quad (5)$$

i.e.

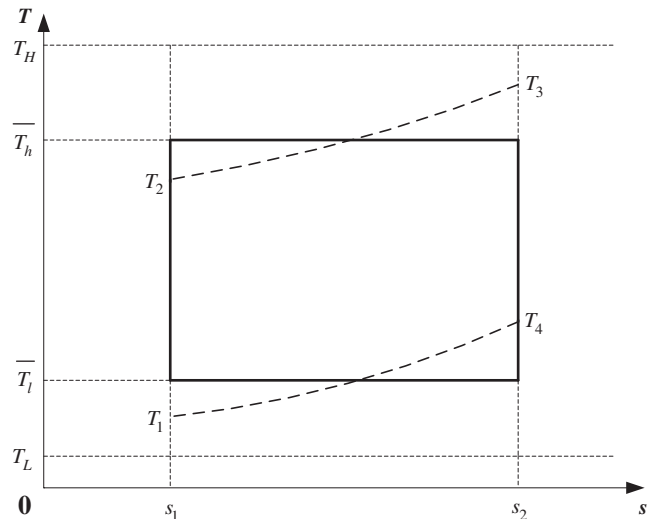


Fig. 7. Thermodynamic cycle process of the gas parcel.

$$\frac{\delta_H}{\delta_L} = \frac{T_H - \delta_H}{T_L + \delta_L} \quad (6)$$

Combining Eqs. (3)–(5), we have

$$\eta = \left(1 - \frac{T_L + 2\delta_L}{T_H}\right) \times 100\% \quad (7)$$

$$P = \frac{h_1 a_1 \delta_L}{2\gamma} \frac{T_H - T_L - 2\delta_L}{T_L + 2\delta_L} \quad (8)$$

Then we define: $\Delta T_{LH} = T_H - T_L$. So

$$\eta = \left(1 - \frac{T_L + 2\delta_L}{T_L + \Delta T_{LH}}\right) \times 100\% \quad (9)$$

$$P = \frac{h_1 a_1 \delta_L}{2\gamma} \frac{\Delta T_{LH} - 2\delta_L}{T_L + 2\delta_L} \quad (10)$$

It is shown that the efficiency of the cycle increases as the gas-stack temperature difference δ_L decrease. As we all know, the gas-stack temperature difference is inversely proportional to the gas-stack heat transfer coefficient h_1 . So we can conclude that the efficiency of the cycle increases as the gas-stack heat transfer coefficient increases.

From Eq. (9), it can be seen that the higher ΔT_{LH} is, the higher the efficiency of the cycle is. As shown in Fig. 6, ΔT_{LH} can be calculated by

$$\Delta T_{LH} = 2A_1(x) \cdot \frac{\Delta T}{l} \quad (11)$$

where $A_1(x)$ is amplitude of the gas parcel, l is the length of the stack, ΔT is the heating difference between the hot and cold heat exchangers. Eq. (11) implies that ΔT_{LH} is proportional to the gas displacement amplitude and the heating temperature difference.

Combining Eqs (9) and (11), we can conclude that the efficiency of the cycle is determined by the gas-stack heat transfer coefficient h_1 , the gas displacement amplitude A_1 and the heating difference ΔT . The higher h_1 , A_1 and ΔT are, the higher the efficiency is.

From Eqs (10) and (11), it can be seen that the acoustic power of the cycle is determined by the gas-stack heat transfer coefficient h_1 , the gas displacement amplitude A_1 , the heating difference ΔT , and the gas-stack temperature difference δ_L . The higher h_1 , A_1 and ΔT are, the higher the acoustic power is.

3.2.2. Explanations of the onset and damping behaviors

Then we can use the above results to analyze the onset and damping behaviors. Before onset, the heat transfer between the gas and the stack is based on natural convection. So the heat transfer coefficient h_1 and the oscillation amplitude A_1 are very low, which makes the thermoacoustic conversion efficiency and the acoustic power very low. As shown in Refs. [26], the thermoacoustic system can be excited when $\overline{W}_s + \overline{W}_{ext} \geq 0$. So a larger temperature difference ΔT should be established to produce enough acoustic power to overcome the work and excite oscillation. Before damping, the gas-stack heat transfer coefficient and the oscillation amplitude are much higher because of the large pressure oscillation, which makes the thermoacoustic conversion efficiency and the acoustic power higher. Thus, a lower temperature difference is needed to maintain the oscillation in damping process. This analysis gives the reason why the onset temperature difference is always higher than the damping one.

After onset, the gas-stack heat transfer is forced convection instead of natural convection. So the heat transfer coefficient and the amplitude of the gas suddenly increase, which lead to sharp

increase of the pressure amplitude and sudden drop of the stack temperature, as shown in Figs. 2 and 3. This is why the onset of the thermoacoustic engine seems to be a sudden process. In the damping process, the gas-stack heat transfer coefficient and the amplitude of the gas decrease gradually. So the damping of the engine is a gradual process.

A similar analysis can be conducted to explain why a contrived pressure disturbance can remarkably decrease the onset temperature. Before onset, the heat transfer coefficient and the gas displacement amplitude are very low. So the efficiency is very low and a little acoustic power is produced by the temperature gradient in this condition. If a contrived pressure disturbance is introduced to the thermoacoustic system, the gas-stack heat transfer coefficient and the gas displacement amplitude are suddenly increased. The efficiency is increased and more acoustic power is produced at the moment. So a lower temperature gradient is needed to produce enough acoustic power to overcome the work loss and the onset temperature is remarkably decreased. Thus, on the premise of not increasing the thermal and viscous dissipation, any method that can increase the heat transfer coefficient between the gas and the stack is possible to be a reasonable way to decrease the onset temperature difference.

3.3. Further verification

The onset and damping behaviors of thermoacoustic engines are so doubtful, further verifications of the above explanations are needed. According to the above explanation, enhancing the natural convection in the stack may be a practical way to increase the gas-stack heat transfer coefficient. In order to change the natural convection in the stack, a series of experiments are conducted at different tilted angles ranging from -90° to 90° , as shown in Fig. 8. When the tilted angle is -90° , the hot heat exchanger is under the cold heat exchanger. In this condition, the direction of the temperature gradient is same as the gravity direction in the thermoacoustic couple. The heated gas in the hot heat exchanger rises constantly to the cold heat exchanger and the natural convection

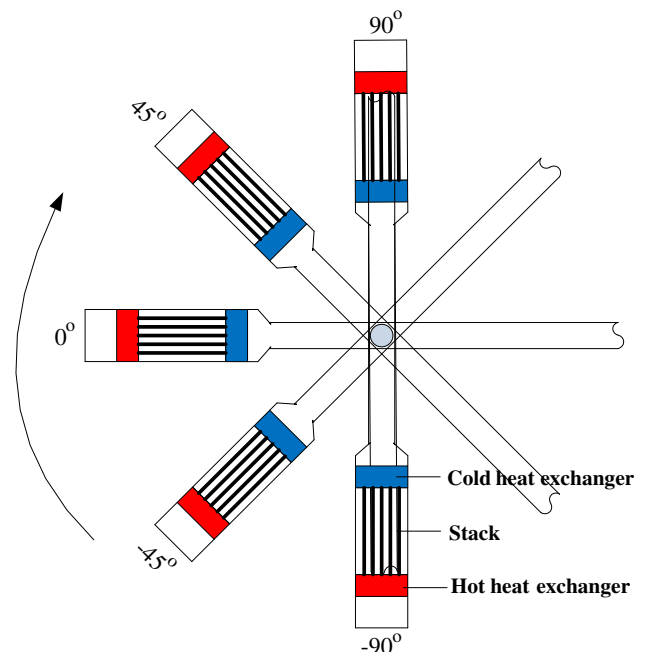


Fig. 8. A schematic diagram of the tilted angle.

between the gas and the stack is greatly strengthened. The natural convection is gradually weakened as the tilted angle increases. When the tilted angle is positive, the gravitational effect goes against the natural convection and the flow within the stack should be weakened. The natural convection and the flow within the stack should be almost completely inhibited when the tilted angle is 90° . So the natural convection and the heat transfer between the gas and the stack are decreased as the tilted angle increases. As suggested by the above explanation, the onset temperature difference should be increased with the tilted angle.

Fig. 9 shows the onset and damping temperatures in the hot and cold heat exchanger when the filling pressure is 1.1 MPa and argon is used as working gas. As it can be seen, the onset and damping temperatures in the hot heat exchanger is lowest when the tilted angle is 0° , which seems to be not conformed to the above analysis. This is because the temperature of the cold heat exchanger is increased by the convection effect and the temperature gradient is hard to establish when the tilted angle is negative, as shown in Fig. 9. In fact, the oscillation in the thermoacoustic engine is excited by the temperature gradient in the stack, but not the temperature of the hot heat exchanger. So the temperature difference between the hot and cold heat exchanger is the only reasonable parameter to measure the onset and damping characteristics in a thermoacoustic engine.

Fig. 10 shows the onset and damping temperature differences between the hot and cold heat exchangers. Both the onset and damping temperature differences are increased with the increasing tilted angle, which are completely in accordance with the above predictions. Additionally, the onset temperature differences are very close to the damping ones when the tilted angle is negative and the tilted angle has more greatly effect on the onset temperature differences than on the damping ones. These phenomena also can be justified by using the above explanations. When the tilted angle is negative, the strong natural convection greatly enhances the heat transfer between the gas and the stack before onset. The gas-stack heat transfer coefficients are close to each other in the onset and damping processes. So the onset temperature differences are approximate to the damping ones when the tilted angles are -45° and -90° . The natural convection is weakened gradually and the gap of the gas-stack heat transfer coefficients becomes greater between onset and damping as the tilted angle increases, which makes the distance between the onset and damping temperature differences larger and larger. In the damping process, the gas-stack heat transfer is greatly enhanced by the oscillation. The natural convection is no longer significant to the gas-stack heat transfer coefficient. So the tilted angle does not have remarkable

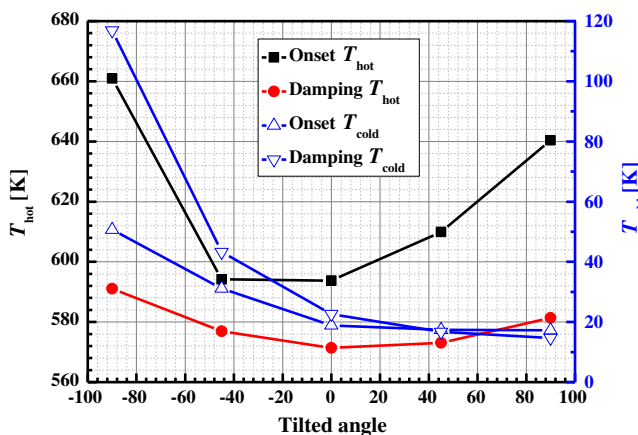


Fig. 9. The onset and damping temperatures of Ar with a filling pressure of 1.1 MPa.

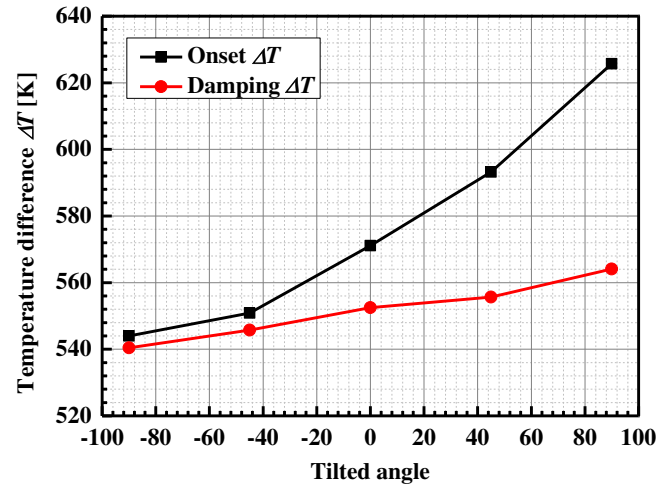


Fig. 10. The onset and damping temperature differences of Ar.

influence on the damping temperature difference, as shown in Fig. 10.

4. Conclusion

In order to understand the onset and damping behaviors of the thermoacoustic engine, a series of experiments and a simplified thermodynamics analysis are carried out. It is found that the thermoacoustic conversion efficiency and the produced acoustic power can be increased by increasing the gas-stack heat transfer coefficient, the gas displacement amplitude and the heating difference.

Based on the above results, a new explanation is proposed to understand the onset and damping process. Before onset, since the gas-stack heat transfer coefficient of natural convection and the amplitude of the gas are very low, a higher temperature difference is required to produce enough acoustic power to overcome the thermal and viscous dissipation and to excite oscillation. In the damping process, the gas-stack heat transfer coefficient and the amplitude of the gas are much higher because of the thermoacoustic oscillation. So a lower temperature difference is required to maintain the oscillation. After onset, the gas-stack heat transfer coefficient and the amplitude of the gas suddenly increase, which lead to sharp increase of the pressure amplitude and sudden drop of the stack temperature. So the onset of the thermoacoustic engine seems to be a sudden process. In the damping process, the gas-stack heat transfer coefficient and the amplitude of the gas decrease gradual. So the damping of the engine is a gradually process. Naturally, a contrived pressure disturbance, which can enhance the heat transfer between the gas and the stack and increase the amplitude of the gas, is a reasonable way to decrease the onset temperature.

Any method, which can increase the gas-stack heat transfer coefficient and the gas displacement amplitude, is a reasonable way to decrease the onset temperature difference on the premise of not increasing the thermal and viscous dissipation. In order to further verify this analysis, experimental investigations are carried out at different tilted angles ranging from -90° to 90° . As the tilted angle decreases, the gas-stack heat transfer coefficient of the natural convection increases. The experimental results show that both the onset and damping temperature differences decreases with the decreasing of the tilted angle, which further confirms the above explanations.

Acknowledgements

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